Search for (B-L) nonconservation in neutron-antineutron transitions

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Abstract. Proton decay into (B - L) conserving modes with rates predicted by the original SU(5) grand unification scheme was not experimentally observed. An alternative possibility for baryon instability corresponding to the nonconservation of (B - L) and evolving at the intermediate energy scale needs to be explored in new experiments. One of the most spectacular manifestations of the physics of such an energy scale would be the observation of neutron-antineutron transitions. Future prospects and discovery potentials of an n -> \bar{n} search are discussed here.

1. Is (B-L) conserved?

Baryon asymmetry of the universe [1] and the ideas of unification of particle and forces [2, 3] are the two global concepts which motivated the experimental searches [4] of baryon instability for more than two decades. Proton decay into (B - L) conserving modes with rates predicted by the original SU(5) grand unification scheme [3] was not experimentally observed. Neutron-antineutron transitions, first considered in [5, 6, 7] within the context of baryon nonconservation concepts and violating baryon number by two units (\Delta B = 2), may be a phenomenon preferred by nature, which is alternative or complementary to the proton decay (\Delta B = 1). An

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extensive recent review of the theoretical and the experimental situation
related to baryon instability search can be found in [8].

Possible nonconservation of baryon number in proton decay is closely
related to the nonconservation of lepton number. Due to conservation of
angular momentum (spin of proton) at least one lepton should be present
in the final state. This creates, in general, two possibilities corresponding
to $\Delta B = \Delta L$ and $\Delta B = -\Delta L$: the first one conserving $(B - L)$ and
the second one violating $(B - L)$ by two units. In a neutron-antineutron
transition, since the leptons are not involved, the $(B - L)$ would be violated
by two units.

The original $SU(5)$ unification model [3], where $(B - L)$ was conserved,
favored the proton decay mode $p \rightarrow e^+ + \pi^0$ with predicted lifetime $\tau/B < 4 \cdot 10^{31}$ years. This model has been ruled out by experiments in which $\tau/B$ was measured to be $> 10^{33}$ years [8]. This situation raises the question
of whether $(B - L)$ is, in general, conserved by nature. It also motivates
the experimental searches for $(B - L)$ nonconserving processes.

There are several reasons to believe that $(B - L)$ might not be universally
conserved.

It was shown [9] that in baryogenesis the nonperturbative Standard
Model effects at electroweak energy scale erase any baryon excess generated
by the $(B - L)$ conserving processes at the earlier moments of the universe
(at $T > 1$ TeV). At the same time, generating baryon excess through
electroweak effects alone does not seem to be adequate to account for the
observed baryon asymmetry and the dark matter in the universe [10, 11].
Thus, a component with $\Delta(B - L) \neq 0$ might be required to explain the
baryogenesis [12].

Standard Model weak interactions are not left-right symmetric like all
other interactions: electromagnetic, strong, and gravitational. It is natural
to think that the restoration of left-right symmetry should take place before
an ultimate unification of all fundamental interaction can occur. In left-
right symmetric unification models, [2, 13] the left-right symmetry is broken
at the intermediate energy scale simultaneously with $(B - L)$ violation
[14, 7]. In such models the transitions $n \rightarrow \bar{n}$, as well as other $(B - L)$
violating processes, might exist with the rates [15] attainable by the modern
experiments.

The smallness of neutrino masses is usually explained by a sea-saw
mechanism (see discussion in [12]) which implies the existence of heavy
right-handed Majorana masses. Majorana neutrinos violate both $L$ and
$(B - L)$ by two units. Some data (particularly the recent LSND results
[16]) calling for rather large $\Delta m^2$ values in a neutrino oscillation scenario,
would require the Majorana masses and the $(B - L)$ nonconservation energy
scale to be in an intermediate range below the grand unification scale.
An alternative interpretation \cite{17} of atmospheric neutrino anomaly \cite{18} in a sub-GeV energy range treats the measured effect not as a dearth of muon neutrinos but as an excess of positron signals in the detectors due to proton decay into the mode $p \rightarrow e^+ + \nu + \nu$. $(B - L)$ is not conserved in such a decay. The “observed” rate of events corresponds to the proton lifetime of $\tau/B \approx 4 \cdot 10^{31}$ years and, from purely dimensional considerations \cite{12}, indicates an energy scale of $\sim 10^6$ GeV of a new physics from which this process originates. The existing lifetime limit for this process is $\geq 1 \cdot 10^{31}$ years \cite{19}.

An interesting possibility which might lead to an alternative mechanism of baryon (and $B - L$) number violating processes has been recently discussed by V. Kuzmin \cite{20}. He assumed that interactions of quarks inside the baryons consisting of quarks from the different families (for example) can be mediated by the family-colored triplet scalar field coupled to the right components of the quarks. For neutral baryons such scalar field interaction might result in fast baryon-antibaryon ($b\bar{u}\bar{s}$) oscillations with a characteristic transition time $\sim 10^{-12}$ s. Such oscillations can be possibly searched at B-factories. The $n \rightarrow \bar{n}$ transition in this model would arise as radiative corrections to this new interaction with suppression of $\sim 20$ orders of magnitude in probability. This will result in an $n \rightarrow \bar{n}$ characteristic transition time of $\tau_{nn} \sim 10^{12}$ s, i.e., close to the existing experimental limits. As mentioned in \cite{20}, the 4-jet events, observed by the ALEPH collaboration at LEP-II \cite{21}, which are peaked at $\sim 105$ GeV, produced with rather high cross section, and have no signature of b-quark jets in the final state, can be explained in this model as a third component production of family-colored scalar-antiscalar.

The arguments presented above, although allowing the alternative interpretations, let us think that the $(B - L)$ might not be conserved and the energy scale corresponding to $(B - L)$ violation can be as low as $\sim 10^5 - 10^6$ GeV. Possible phenomena related to $\Delta(B - L) \neq 0$ would include: proton decay into modes $N \rightarrow l + mesons$ and $N \rightarrow l\bar{l} + (mesons)$; Majorana masses for the neutrinos; neutrinoless double beta decay; transitions $b\bar{u}\bar{s} \rightarrow \bar{b}\bar{u}\bar{s}$; intranuclear transitions of two nucleons into pions; and $n \rightarrow \bar{n}$ transitions in vacuum. The question of whether such physics exists can be answered only experimentally. If it does exist, the experimental observation of $n \rightarrow \bar{n}$ transitions with free neutrons from reactors will be its most clear and spectacular manifestation since (a) the detection signal for an $n \rightarrow \bar{n}$ transition is clean and unambiguous and (b) the discovery potential (see definition below) for an $n \rightarrow \bar{n}$ search can be experimentally improved by a large factor relative to the present experimental limits \cite{19}. 

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2. Present status of $n \rightarrow \bar{n}$ search

The $n \rightarrow \bar{n}$ transitions can be searched (a) by utilizing free neutrons from reactors or neutron spallation sources and (b) with neutrons bound inside the nuclei.

The yield of antineutrons $N_n$ in a beam of free neutrons in a vacuum (in the absence of external fields) due to $n \rightarrow \bar{n}$ transitions depends on the observation time $t$ as $N_n \propto N_n \cdot (t/\tau_{nn})^2$ \cite{7}, where $N_n$ is the number of neutrons used in an experiment and $\tau_{nn}$ is the characteristic $n \rightarrow \bar{n}$ transition time. It is assumed in this expression that neutrons and antineutrons have equal masses as required by CPT theorem. In this way the discovery potential of an $n \rightarrow \bar{n}$ search experiment is proportional to the neutron flux and to the square of the neutron time-of-flight $N_n t^2$. High steady-flux reactors together with cold neutron moderators, which slow down the velocities of neutrons, would be, therefore, most appropriate for an $n \rightarrow \bar{n}$ search.

The general scheme of an $n \rightarrow \bar{n}$ vacuum transition search is the following: neutrons emitted from the cold moderator are propagating in the vacuum volume (shielded against earth's magnetic field down to the level of a few nT) where the $n \rightarrow \bar{n}$ transition occurs. Produced antineutrons propagating along the initial neutron direction would be detected as a few-meson star with a total energy release of $\sim 1.8$ GeV resulting from the antineutron annihilation with a thin target film.

The recent most advanced experimental search for $n \rightarrow \bar{n}$ with free neutrons was performed \cite{22} at the 58 MW research reactor at the Institute Laue-Langevin (ILL) in Grenoble. The experiment had a discovery potential of $N_n t^2 \sim 1.5 \cdot 10^9$ seconds and for one year of operation set a limit of $\tau_{nn} \geq 8.6 \cdot 10^7$ s.

Intranuclear transition time $\tau_A$ is related to free neutron transition time $\tau_{nn}$ as $\tau_A = T_R \cdot (\tau_{nn})^2$, where $T_R$ is the nuclear suppression factor. This factor has been evaluated by several authors during the last two decades. Most recent discussions and new reevaluations, as well as references to the previous works, can be found in \cite{8}. According to \cite{23}, for oxygen, argon, and iron the suppression factor has a value $T_R \sim 2 \cdot 10^{23}$ s$^{-1}$.

Experimentally, the intranuclear $n \rightarrow \bar{n}$ transitions have been searched in the nucleon stability experiments IMB, Kamiokande, and Fréjus \cite{19}. The best limit for the intranuclear $n \rightarrow \bar{n}$ transition lifetime was set by a Fréjus experiment for iron nuclei. It is $\tau_{iron} \geq 6.5 \cdot 10^{31}$ years and, according to the suppression factor from \cite{23}, corresponds to $\tau_{nn} \geq (0.8 - 1.0) \cdot 10^8$ s.

During the next decade, the large new detectors SuperKamiokande and Icarus might improve the intranuclear $n \rightarrow \bar{n}$ transition limit. Thus, after a few years of operation, the SuperKamiokande detector (which was commissioned in April 1996) will be able to set an $n \rightarrow \bar{n}$ transition limit of $\tau_{oxygen} \geq 10^{32}$ years \cite{24}.
The relative potentials of different methods for an n → $\bar{n}$ search were discussed in [25]. It is possible experimentally to improve the discovery potential for this process by a significant factor, $\sim 1,000$ relative to the existing experimental level both for vacuum n → $\bar{n}$ oscillations and for intranuclear transitions. These two new possibilities are discussed below.

3. New experiment with free neutrons

A new experiment for an n → $\bar{n}$ search at the 100 MW HFIR reactor at Oak Ridge National Laboratory was proposed by a UT-ORNL group [26]. The major improvement in the discovery potential [27] is based on the properties of neutrons to be focused by means of reflection from the surfaces of certain materials. In this new approach an elliptically-shaped reflector intercepts the neutrons emitted from the cold source within a large solid angle and focuses them on the annihilation target situated at a distance of $\sim 250$ m from the source.

Schematic layout of the proposed HFIR-based experiment is illustrated in Figure 1. The gain in discovery potential (relative to the ILL-based experiment [22]) will result from the following factors: higher reactor power, larger area of the cold neutron emitting source, larger area of the annihilation detector, but, most essentially, from the use of a large-acceptance elliptical focusing reflector. For three years of operation at HFIR the discovery potential can be increased by a factor of $\sim 1,000$ relative to the discovery potential of [22].

Figure 1. Conceptual layout of the experiment with a large elliptical focusing reflector for an n → $\bar{n}$ transition search at the HFIR reactor (not to scale).
4. Intranuclear search with rare isotopes

A new approach to an intranuclear $n \rightarrow \bar{n}$ transition search has been recently proposed in [28]. This approach is based on the measurement of the concentration of the long-lived rare isotopes (with a lifetime in the range of million years) which can be the remnants of intranuclear $n \rightarrow \bar{n}$ transitions accumulated among the parent nuclides contained in the nonradioactive deep-mined ore. As an example, the search for technetium isotopes $^{97}\text{Tc}$, $^{98}\text{Tc}$, and $^{99}\text{Tc}$ in tin ore was considered in [28]. The extraction of technetium from the large volumes of tin ore is envisaged as a nonexpensive by-process of standard industrial smelting of tin. Final separation and count of technetium atoms were assumed to be made with an overall efficiency of $\sim 1\%$ by a combination of chemical and selective laser photoionization spectroscopy methods. Major sources of background are (a) the admixture of or the contamination with spontaneously fissionable nuclides and (b) nuclear transmutations caused by inelastic interactions of cosmic muons in ore deposits. The discovery potential in this approach (see Figure 2) is determined by these background processes and can be different for different ore deposits.

![Figure 2](image_url)

**Figure 2.** Discovery potential of rare isotope methods expressed in tons of initial tin ore required to be processed in order to set 90% CL limit on intranuclear $n \rightarrow \bar{n}$ transitions in tin (see explanations in the text).
Two background scenarios, considered in [28] and called as optimistic and pessimistic in Figure 2, correspond to tin deposits with a U concentration of 10 ppb and a depth $\sim 3.2$ km of the rock and a U concentration of 1 ppm and a depth $\sim 1.6$ km of the rock. Thus, the extraction and analysis of technetium isotopes $^{97}\text{Tc}$ and $^{98}\text{Tc}$ from $\sim 10,000$ tons of concentrated tin ore can provide a limit for an intranuclear $n \rightarrow \bar{n}$ transition in the range of $\tau_{\text{Tin}} \sim 10^{23} - 10^{34}$ years.

5. Summary and future prospects

The potentials and prospects of different methods for $n \rightarrow \bar{n}$ transition searches are summarized in Figure 3 where the free neutron experiments are related to those for intranuclear transitions via the formula $\tau_A = T_R \cdot (\tau_{\text{nn}})^2$ (with suppression factor $T_R$ from [23]) which gives an opportunity to compare different experimental methods.

![Figure 3. Comparison of $n \rightarrow \bar{n}$ search in intranuclear transitions ($\tau_A$) to those in free neutron experiments ($\tau_{\text{nn}}$). The slope and the width of the nuclear model band connecting these two processes corresponds to $\tau_A = T_R \cdot (\tau_{\text{nn}})^2$, where $T_R$ is the nuclear suppression factor taken from [23].]
At the present time the experimental free-neutron transition limits and the limits from intranuclear transition experiments correspond to each other. If the experimental limits for an intranuclear transition (in Super-K and by rare isotope method) will be improved to the level of $10^{33} - 10^{34}$ years, this would correspond to an equivalent limit for the free-neutron transition time of $4 \cdot 10^8 - 10^9$ s. Future spallation source or reactor-based experiments with free neutrons have much higher discovery potential and can realistically set the limit for transitions between $10^6$ and $10^{10}$ s. In the future, if all experimental possibilities will be stretched to their limits, the $n \rightarrow \bar{n}$ search can be ultimately extended to the probability levels corresponding to the transition time of $10^{11}$ s [27]. Such experiments will allow exploring the stability of the matter, although in only one particular mode, but beyond the limits attainable in proton decay search experiments.

The current phenomenology of $n \rightarrow \bar{n}$ transitions is based on the assumption that neutrons and antineutrons have equal masses (as required by CPT conservation) and that the gravitational interaction with the earth is the same for neutrons and antineutrons. These assumptions, although perfectly acceptable by contemporary theoretical schemes, require, in themselves, experimental confirmation.

It was pointed out in [29] that a positive observation of $n \rightarrow \bar{n}$ transitions would allow testing a CPT theorem (which requires that the mass of a particle is equal to the mass of a corresponding antiparticle) with unprecedented accuracy. A similar conclusion can be drawn regarding the difference of gravitational interactions of neutrons and antineutrons.

The presence either of a mass difference, $\Delta m$, or of a gravitational interaction difference of neutrons and antineutrons would result in the suppression of transitions of free neutrons to antineutrons. The intranuclear transitions, as was pointed out in [29], are not additionally suppressed by these effects. The latter takes place due to the fact that the mass difference, or the difference in the gravitational potentials of neutrons and antineutrons, is considerably less than the difference of neutron and antineutron nuclear potentials (in a MeV range). The experimental observation of intranuclear transitions together with the suppression of the corresponding rate of transitions in experiments with free neutrons would indicate the presence of $\Delta m$ or a difference in gravitational interactions. If both types of experiments could measure matching transition rates, it would allow setting unprecedentedly low limits on $\Delta m$ or on the difference of gravitational interaction of particles and antiparticles. The $\Delta m$-sensitivity in such a case would be of the order of $1/t$, where $t$ is the time of free neutron observation in the experiment. In the proposed HFIR-based experiment, $t \sim 0.3$ s and the corresponding $\Delta m/m$ sensitivity can be at the level of $\sim 10^{-24}$. Both kinds of $n \rightarrow \bar{n}$ search experiments (intranuclear and with free neutrons) are necessary in order to address the question of the neutron and antineu-
tron mass difference. Following the considerations of papers [29], Figure 4 illustrates the $\Delta m/m$ limits currently available from measured neutron-antineutron, proton-antiproton, and $K^0 - \bar{K}^0$ mass differences together with the limits which can be established through an $n \to \bar{n}$ oscillation search.

**Figure 4.** The mass difference $\Delta m$ (not allowed by CPT theorem) between particle and antiparticle would suppress the vacuum $n \to \bar{n}$ transition amplitude $\alpha$. Observation of $n \to \bar{n}$ transitions in free-neutron and in intranuclear experiments will provide, according to [29], a sensible test of CPT.
6. Conclusions

Long-awaited baryon instability of the type suggested by the original SU(5) unification model with \((B - L)\) conservation was not observed experimentally. The new generation of experiments (Super-Kamiokande and ICARUS) will continue the quest for most sophisticated baryon instability schemes and within the next decade will bring it to the limits which will be probably difficult to stretch further by still larger experiments. An alternative possibility of the existence of baryon instability processes with \((B - L) \neq 0\) has been emphasized in this paper. If discovered, the \(n \rightarrow \bar{n}\) transition will point to the new domain of physics at the energy scale \(\sim 10^5\) GeV. In this domain new symmetry principles may be revealed which can restore the left-right symmetry broken in the Standard Model and explain the neutrino mass hierarchy; most essential aspects of unification theories and cosmology will be affected.

There is an experimental possibility to increase the discovery potential for a neutron-antineutron transition search, with presently existing neutron sources and at the present level of technology, by a factor of \(10^3 - 10^4\) and, with future technology advances and new neutron sources, probably by another factor of \(\sim 100\). If neutron-antineutron transitions are discovered, it will open a unique experimental possibility to test CPT symmetry of nature and to establish gravitational equivalence of matter and antimatter.

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References

[1] Sakharov A D 1967 JETP Lett. 5 24


Takita M 1997 these proceedings


[26] Bugg W M et al 1996 Letter of Intent to the Oak Ridge National Laboratory to Search for the n → n Transition Using a Detector to be Built at ORNL's High Flux Isotope Reactor (UTK-PHYS-96-L1)